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Comfort filters in a total energy demand optimization method for the passive design of a building

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Abstract

The effective design of sustainable buildings results from an accurate optimization process of all the interrelated variables. The authors developed a replicable methodology for the optimization of the building envelope design.
Following a previous work, where in the pre-processing and the optimization phases the minimization of the total energy demand is performed by coupling TRNSYS® with GenOpt®, this paper is focused on the post-processing phase of the methodology, in which the results are validated and the comfort filters are applied. As an explanatory example, the application of the methodology to a school classroom located in two different climates is presented.

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Keywords: integrative design; optimization; sensitivity analysis; thermal comfort; visual comfort; building envelope; school classroom; TRNSYS; GenOpt; total energy.

1. Introduction

The current challenge of reducing the environmental impact of the construction sector, addressed by many European Directives (2010/31/UE, 2012/27/UE et al.), requires that the building industry moves towards more sustainable practices and clear and quantifiable targets for building design. The complexity of these goals strongly encourages the integrative design and a better cross-disciplinary approach. In this field, the integrative design can help in effectively managing and optimizing synergies between the complex set of technical systems associated with

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the sustainable building performance. Project team members look for synergies among systems and components, and the mutual advantages that can help achieve high levels of environmental, social and economic performance [1].

The integrative design approach should favour achieving technical requirements focusing on indoor air quality, visual and thermal comfort and need for heating and cooling, which are largely influenced by the passive qualities of the building, including geometry and material properties.

Within this framework, an optimization approach may be used to map out and find the best set of solutions that guarantee the design of buildings with high performance and desirable qualities. Traditional parametric studies, that involve changing one parameter at a time while leaving the others constant [2], are not reliable, since important interactive effects can potentially be missed. One way to find a global optimum is to use enumerative search methods where each possible parameter setting is combined with one another, generating many design options [3].

All these challenges have made it advantageous to apply building computational methods of design optimization. All major issues are developed in parallel with each other, so that the design team can identify cross-linked interrelationships and resultant benefits. In order to perform an accurate optimization, it is necessary to evaluate a great number of design options, which is often time-consuming: to achieve an optimal solution to a problem (or a solution near the optimum) with less time and labour, the computer building model is usually “solved” by iterative methods, which construct sequences, of progressively better approximations to a solution, i.e. a point in the search-space that satisfies an optimality condition. Due to the iterative nature of the procedures, these methods are usually automated by computer programming. Such methods are often known as “simulation-based optimization”[4]. In building optimization studies, this process is usually automated by the coupling between a building simulation program and an optimization ‘engine’, which may consists of one or several optimization algorithms or strategies.

Reviewing the computational optimization methods that are applied to sustainable building design by Nguyen et al. [5] and Evins [6], about 60% of the building optimization studies use the single objective approach (energy demand in 60% of cases followed by costs objectives), while the others consider a multi-objective approach [7].

1.1. Scope of the work

Scope of the work is to set up a methodology able to support the integrative design process, which aims at optimizing the energy performance in a context of indoor thermal and visual comfort conditions. Previous work in this field presented by the Authors are in [8] and [9].

The methodology focuses on the optimization process of the passive design of a building taking into account a large number of variants concerning the building envelope design (window-to-wall ratio, glazing and opaque envelope type, fixed exterior shading, solar absorption coefficient). The selected set of solutions are those that will minimize the energy demand, taking into account also two other objectives (or a combination of them) representing thermal and visual discomfort.

The study tests the potentialities of the methods on a simple case-study of a school classroom, in two different climates (Turin, northern Italy, and Palermo, southern Italy) for a south orientation.

The optimization methodology integrates several tools, aiming at identifying:

- the set of design options minimizing the total primary energy need, intended as the sum of energy needs for heating, cooling and artificial lighting (energy optimal solutions);
- among the energy optimal solutions, the set of design options maximizing the thermal comfort and the visual comfort (comfort filters).

As a results, the set of design options that satisfy at the same time the requirements related to energy efficiency and comfort are selected.

The implementation of such procedure into the early design concept will lead to a more cost-effective design since it’s well proven that changes and improvements of the design are relatively easy to make at the beginning of the design process, but become increasingly difficult and disruptive as the process unfolds.

The final objective is to provide a tool for supporting the building design by providing information on how much some specific design choices can influence the final performance of the building. In this way, the human is supported in the decision rather than being constrained by the and not computer results. In fact, the methodology was set so that the pre-processing, the post-processing and the set of boundary conditions clearly depend on the human decision.

Nomenclature

D_m	Mean daylight factor
PE	primary energy demand (*tot* – total; *heat* – heating; *cool* – cooling; *light* – lighting; *opt* – optimal)
TDI	thermal discomfort index
t_o	operative temperature

2. Methodology

The optimization process is subdivided in three phases, including a pre-processing phase, an optimization phase and a post-processing phase. The overall methodology, from pre-processing to post-processing, is shown in Fig. 1.

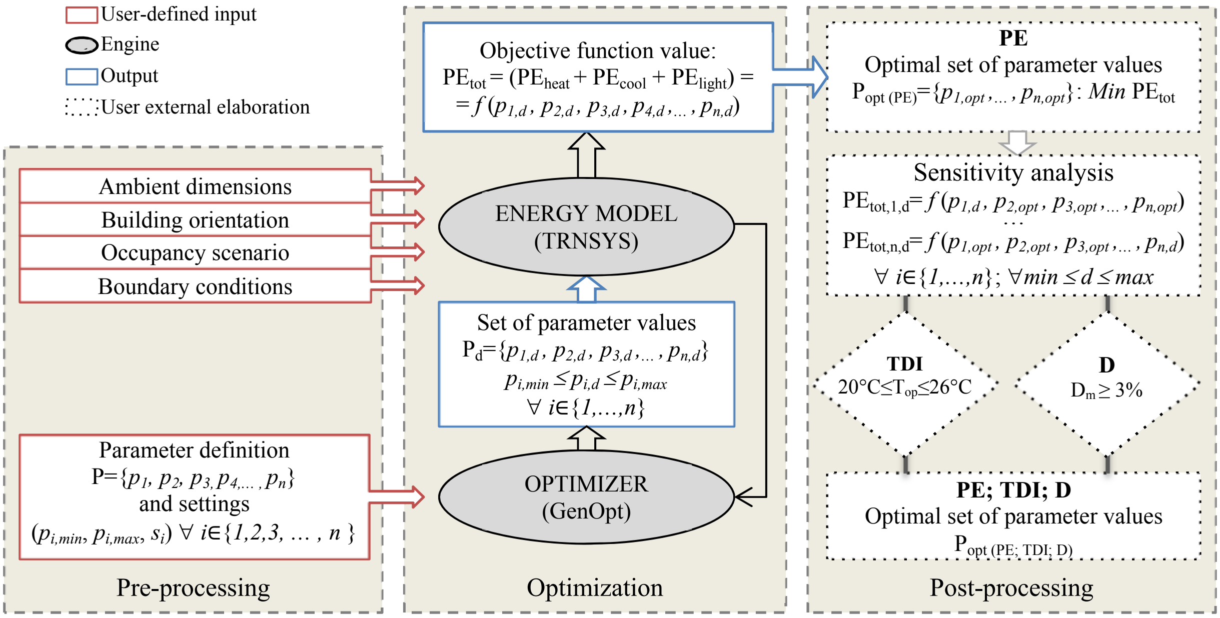


Fig. 1. Pre-processing, optimization and post-processing phases of the proposed methodology for the total energy demand optimization

The pre-processing phase includes the definition of the boundary conditions, the creation of the computer building model, the selection and setting of the design variables related to the building envelope and their constraints. The building design optimization problem, from the total energy point of view, can be stated as follows:

$$\begin{array}{llll} \text{Find} & p_{i,d}\ \forall i \in \{1,2,3,\dots,n\} & \text{such that} & f\colon min\{PE_{tot}(\mathbf{P})\} \\ \text{Subject to} & \mathbf{P} = \{p_1, p_2, p_3, \dots, p_n\} \subset \mathbb{Q}^n & & \\ & p_{i,min} \le p_{i,d} \le p_{i,max} & & \forall i \in \{1,2,3,\dots,n\} \end{array}$$

Where P is the set of *n* user-defined envelope design parameters *p*, $p_{i,d}$ denotes a value assumed by the parameter p_i in a potential solution P_d. Since all the design parameters p are discrete variables, $p_{i,min}$ and $p_{i,max}$ are defined respectively as the lower and the upper values of the parameter interval of variation and s_i is the number of discrete steps in which the interval between $p_{i,min}$ and $p_{i,max}$ is subdivided.

Considering the complexity of the problem (the high number of design variables and the complexity of the calculation), the methodology is supported by the use of dynamic simulation software and algorithms for optimization. In this work, the coupling of the building dynamic simulation program TRNSYS® with the Generic Optimization program GenOpt® is performed. In the optimization phase, the optimization algorithm of GenOpt selects a set of parameter values to be entered to TRNSYS, which performs the simulation and calculates the value of the objective function depending on that parameter set. After registering the objective function value and the related parameter values set, GenOpt, driven by the selected optimization algorithm, defines another parameter values set to re-start the simulation, following this iterative process until the stopping criteria is met and the objective function PE_{tot}, representing the total energy demand for heating, cooling and lighting, is minimized.

Finally, two steps are included in the post-processing phase. First, the effectiveness of the optimization process and the robustness of results is verified through sensitivity analysis. Then, among the resulted optimal solution from the energy point of views, the methodology introduces a second level of optimization objective, leading the choice of the best set of solutions by applying some “comfort filters”, that are related to the thermal and visual comfort.

3. Application of the methodology

The methodology has been tested on a case study, which was selected because of its standardization features and the consequent high replicability potential.

3.1. Pre-processing: the case study and the parameter definition

The case study model (CSM) is a typical classroom in linear plan schools, served by a single-loaded or double loaded corridors. The classroom fixed dimensions are: 7,5 m (w) × 8 m (l) × 3 m (h) for a total floor area of 60 m^2. The surfaces bordering the outdoor environment are the south-oriented exterior façade and the roof, while the others are adjacent to rooms conditioned at the same indoor air temperature. There are no external frontal obstructions.

According to the occupant density given by the Standard UNI 10339, the occupancy was set to 27 people and the related ventilation rate was set to 3.5 ach. The occupation time is set 8 am–18 pm, Monday through Friday in all months of the year except July and August. Lighting and appliance gains follow the same occupancy schedules.

According to the Italian regulations UNI-TS 11300, the set-point temperature for the conditioned space was set to 20°C in winter and 26°C in summer. The primary energy needs were calculated considering an ideal energy system.

In this study, the optimization process and the post-processing analysis were conducted for two different climatic context: Turin (Piedmont, Italy) represents the continental Europe climatic conditions, while Palermo (Sicily, Italy) represents the Mediterranean ones. IWEC weather data were used.

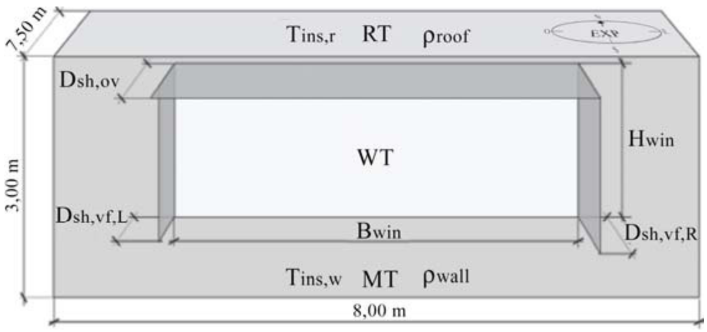


Figure 1. Representation of the case study model (CSM) with related design parameters, reported in details in Tables 1, 2, 3, 4, 5

The pre-processing stage of the methodology deals mainly with the definition of the optimization parameters, which are related to the classroom’s components geometry, or its envelope system. The identified parameters are represented in Fig.1 and reported in details in Table 1. The range and step of their variation were defined according to current construction practice. Geometry and material properties parameters follow a discrete step variation within a specific range, where the lower parameter values were set according to the current Italian regulatory requirements (e.g. minimum U-value of opaque and transparent envelope for the two different climatic zones).

The envelope typology parameters are defined as choice between options. The first envelope system (M1, M3, R1, R3) is a heavy solution, which considers concrete blocks and slabs with external insulation. The other envelope system (M2, M4, R2, R4) is a lightweight wooden structure. The insulation thickness of both envelope systems can vary during the optimization process (parameters Tins,w - Tins,r). Details are reported in Tables 2-3 (Appendix A).

Windows may vary their dimensions (parameters Bwin, Hwin) and type (parameter WT). The choice of the different window options was led by the aim of evaluating the combined effect of different level of insulation (U-value), solar control (g-value) and visual transmittance capability (□ glass), on the total energy demand and daylight availability. Detailed window typologies are reported in Tables 4-5 (Appendix A).

Parameters Dsh,ov, Dsh,vfL and Dsh,vfR control the dimension of the fixed shading systems (respectively the horizontal overhang, left and right vertical fins), which are considered as totally opaque.

3.2. Optimization

As previously introduced, the coupling between TRNSYS and GenOpt ensured the easy and fast run of multiple simulations. Among those available in GenOpt, the particle swarm optimization algorithm (PSO) was selected. Each optimization process resulted in 1600 simulations (100 generations), each corresponding to a different design option.

According to the methodology developed, the objective function is the total annual energy need of the CSM, which is composed by heating, cooling and lighting needs. An ideal energy system was considered and the different energy needs were added together in terms of primary energy using the equation (1), where the heating energy is weighted with a conventional energy efficiency η=1 and a primary energy factor of 1 (gas condensing boiler), the cooling energy is reported into electricity considering a seasonal energy efficiency ratio (SEER) equal to 3 (air cooled chiller) and then weighted with a primary energy factor equal to 2.18 (standard Italian conversion factor), the lighting energy is multiplied by the primary energy factor for electricity.

$$PE_{tot} = PE_H + PE_C + PE_L = Q_{heat} \cdot 1 + \frac{Q_{cool}}{3} \cdot 2.18 + Q_{light} \cdot 2.18 \qquad [kWh \cdot m^{-2}] \quad (1)$$

3.3. Post processing

The first stage included in the post-processing phase is the performing of a sensitivity analysis on the results, which is done by varying the value of one parameter at a time from its minimum to its maximum value, while the others parameters are fixed to their optimal value found in the optimization phase. Given that the optimization process should result in the optimal set of parameter values related to the minimized objective function, the variation of each parameter within the sensitivity analysis should only cause the objective function increase. This allows to verify whether the solution found by the optimization is highly reliable and robust. Moreover, it allow to assess the effect of the variation of each parameter, considered one by one, on the heating, cooling and lighting energy needs and, as a consequence, on the total primary energy demand.

As second step, among the resulted energy optimal solutions, the methodology introduces a second level of optimization objective, leading the choice of the best set of solutions by applying some “comfort filters”.

Concerning the thermal comfort, the index used to evaluate the performance of the selected solutions is compliant with the *Method A. Percentage outside the range* presented in Annex F of the Standard UNI EN 15251. The thermal discomfort index TDI_{t_o} calculates the number or percentage of occupied hours O_h (those during which the building is occupied) when the calculated operative temperature t_o is outside a specified acceptable range. The operative temperature t_o represents an ambient mean value as it is calculated hour by hour at the air node of the thermal zone.

Therefore, the thermal discomfort index is defined as follow:

$$TDI_{t_o} = \frac{\sum_1^{Oh}(w_i \cdot h_i)}{\sum_0^{Oh} h_i} \in [0; 1] \quad (2)$$

Where the weighting factor w_i, assumes these following values:

$$w_i = 1 \leftarrow (t_o < t_{o,min}) \vee (t_o > t_{o,max}) \quad (3)$$

$$w_i = 0 \leftarrow (t_{o,min} \le t_o \le t_{o,max}) \quad (4)$$

In this study, the acceptable range of t_o is defined according to the category II of the Standard UNI EN 15251 ($t_{o,min} = 20°C, t_{o,max} = 26°C$), while the acceptable value of the thermal discomfort index is $TDI_{to} < 10\%$.

The visual comfort performance is evaluated considering the value of the D (Daylight factor), whose calculation is implemented in TRNSYS at each step in accordance to the Standard EN 15193, Annex C. Acceptable value of D are defined in the range 3%-4%.

4. Results

4.1. Total energy optimal solutions

The graphs in Fig. 2 show all the design options simulated for Turin and Palermo, ordered according to the objective function values, from highest to lowest.

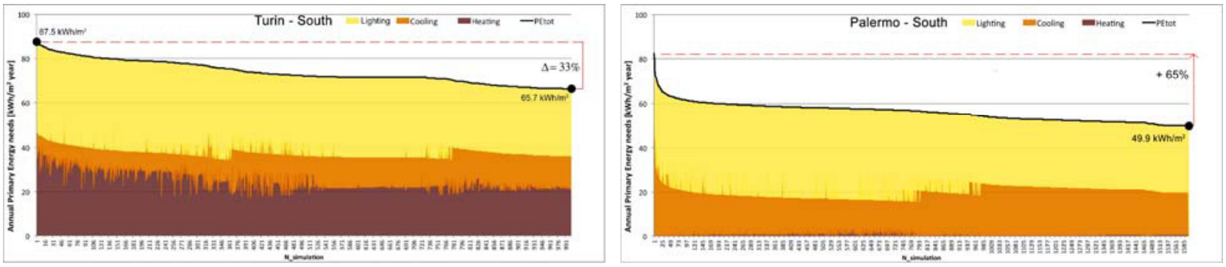


Fig. 2. All design solutions evaluated by the optimization process, from highest to lowest objective function values. (a) Turin, (b) Palermo.

It is clearly shown that the optimization process was able to find design options that significantly minimize the objective function value. The gap between the highest and lowest energy demand value of the simulated design options is around 33% in Turin and around 65% in Palermo. This gap is referred to the minimum objective function value, calculating in terms of percentage how much it increases in the design option corresponding to the highest evaluated objective function value. This allows quantifying the decrease of the building performance that may occur if the design is not accurately optimized.

Similar values of PEtot are composed by different share of cooling, heating and lighting needs. The weight of each use on the total energy demand depends on the climatic conditions. In this case study the lighting energy always accounts for the higher value in both the climatic context, followed by the heating energy in Turin and cooling energy in Palermo. Furthermore, the assumed daily occupancy scenario causes heating needs to be close to zero in Palermo, as the internal occupancy gains compensate the thermal loss, leading the building to have a passive behavior in winter. During the optimization process, PELight assumes three different values (40.9 kWh/m^{2}y, 35.9 kWh/m2y, 30.1 kWh/m^{2}y) that correspond to the three interval of daylight factor classification "Weak" ($1\% \leq D < 2\%$), "Medium" ($2\% \leq D < 3\%$), "Strong" ($D \geq 3\%$), defined in the Standard UNI EN 15193 and recognizable in the three steps of the clearest part in diagrams of Fig. 2. In Table 6, the values assumed by the design parameters in the design option corresponding to the minimized total energy demand are reported.

Table 6. Parameter values related to energy optimal design options for Turin and Palermo

	Energy demand				**Comfort**		**Opaque envelope**						**Transparent envelope**			**Shadings**		
	PE_{tot}	**PE_{heat}**	**PE_{cool}**	**PE_{light}**	**TDI**	**D**	**$T_{,ins,w}$**	**$T_{,ins,r}$**	**MT**	**RT**	**$\rho_{,wall}$**	**$\rho_{,roof}$**	**WT**	**H_{win}**	**B_{win}**	**$Dsh_{,ov}$**	**$Dsh_{,vf,}$**	**$Dsh_{,vf,R}$**
	[kWh/m^{2}y]				[%]		[m]	[m]	[-]	[-]	[-]	[-]	[-]	[m]	[m]	[m]	[m]	[m]
Turin	**65.7**	21.5	14.1	30.1	48	3.01	0.21	0.21	M1	R1	0.2	0.2	W4	1.00	7.00	0.00	0.00	0.20
Palermo	**49.9**	0.6	19.2	30.1	49	3.01	0.01	0.01	M3	R3	0.2	0.2	W6	1.00	5.00	0.20	0.00	1.00

4.2. Post-processing: sensitivity analysis

The results of the sensitivity analysis are reported in Fig. 3 (Turin) and Fig. 4 (Palermo).

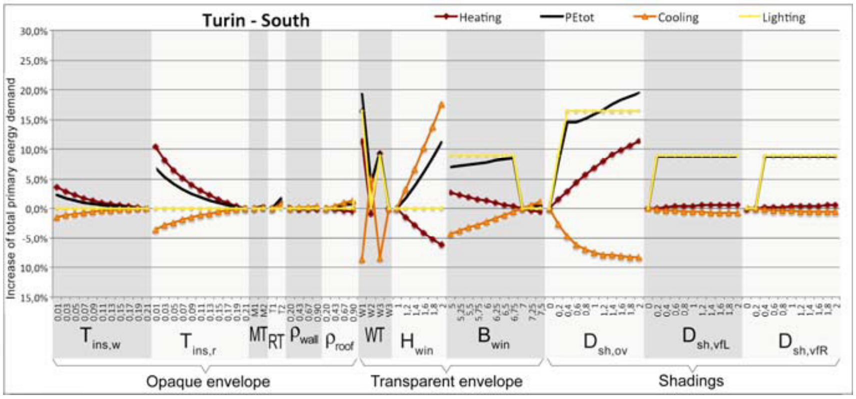


Fig. 3. Turin - South orientation | Sensitivity analysis

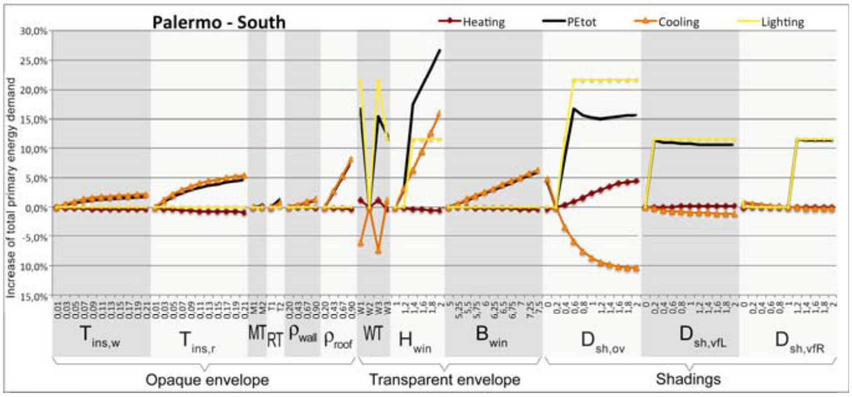


Fig. 4. Palermo - South orientation | Sensitivity analysis

The diagrams show on the x-axis the steps of variation of each parameter considered in this study, while on the y-axis the increase of the energy needs caused by the parameter variation is reported in relation to the resulted optimal objective function value. The curves corresponding to the contribution of heating, cooling and lighting needs on the total energy variation are also reported. Therefore, the resulted optimal values of each parameter correspond to the point of the different curves laying on the x-axis, where the energy demand increase is equal to zero. The fact that there are no values of the PEtot curve below the x-axis confirms that the optimization process effectively minimized the objective function and that all parameter values variations increase the objective function value.

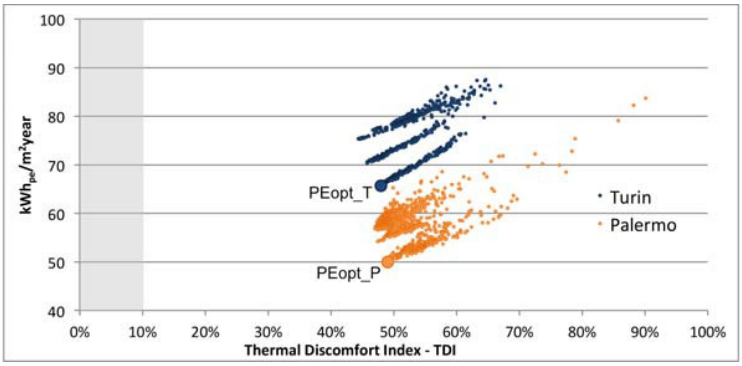
Concerning the opaque envelope parameters, it is demonstrated that the insulation increase has opposite effects in the two locations, as in Turin, which is heating-driven, the thicker the insulation, the lower the total energy demand; while in Palermo, which is cooling-driven, the thicker the insulation, the higher the total energy demand. Furthermore it is shown that, for the same parameter values, changing from massive to lightweight envelope (parameters MT and RT) causes a not significant total energy demand increase. The opaque envelope absorption coefficient variation has a significant impact only in Palermo, where higher values of parameters ρ_{roof} and ρ_{wall} causes higher cooling loads and thus the total energy demand increase by around 8%. This increase is higher for absorption coefficient of the roof, as it received a higher amount of solar radiation.

Concerning the window type parameter (WT), in both locations, the window type having the highest U value and the lowest τ and g values (window W1 for Turin and window W5 for Palermo) causes the highest increase in total energy demand in all orientations. With respect to this window types (W1 and W5), it is interesting to note that window types having higher τ and g values but the same high U values (W2 and W6) perform better than window types having a lower thermal transmittance but the same low τ and g values (W3 and W7). This demonstrates the importance of a window design that considers all these features and not only the thermal transmittance value.

Considering the window dimension parameters (Hwin and Bwin), in Palermo, the more the objective function increase. This is due to the bigger amount of solar energy entering the ambient, as the greater the window the higher the cooling needs. For what concerns the window width parameter (Bwin) in Turin, the parameter optimal value corresponds to a high window width, which cause the lighting energy needs to decrease falling in the lower range (cfr. 4.1). The change of lighting interval is also visible in the shadings parameters. In both locations, however, the horizontal shading (parameter Dsh,ov) has the greater impact. In Turin, high depth of the horizontal shading increases by almost 20% the total energy demand, because of the role of solar gains in winter.

4.3. Post-processing: the comfort filters

For applying the comfort filters, all the simulated design options are reported as "clouds" in diagrams having on the x-axis the comfort index (TDI in Fig. 5, D in Fig.6), and on the y-axis the total primary energy demand. The range of acceptable comfort conditions is reported as a grey region. As shown in Fig.5, the cloud related to the thermal comfort is far from the grey region (TDI< 10%). This indicates the need of a comfort control operated by an energy system. However, the PE_{opt} points in both locations are located in the left part of the cloud, where the best comfort conditions occurs. On the other hand, the PEopt points in both locations fall within the acceptable range of the daylight value (3% < D < 4%), as shown in Fig. 6. Better daylight performance may be reached with a little PEtot increase. It is interesting to note that the clouds report many points having the same comfort conditions, but higher total energy needs than the PEopt points. This confirms the effectiveness of this integrated approach, as a design approach only focused on the comfort performance may result in non optimal energy performance, for the desired comfort conditions.



. Fig. 5. The thermal comfort filters clouds for Turin and Palermo

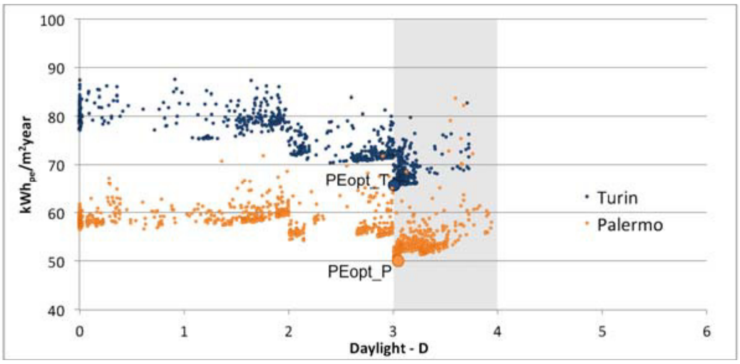


Fig. 6. The visual comfort filters clouds for Turin and Palermo

5. Conclusions

An original method for the optimization of the energy design of an enclosure based on the minimization of the total primary energy use and the application of filters on the thermal and visual comfort was developed and applied to the optimization of the design of a classroom.

This method has been proved to be useful for the determination of a set of optimal solutions that are helpful to make decision in early design stage. It is noted that most of the resulted solutions are in trend with the general know-how about the passive design of buildings (massive envelopes to ensure inertial effects in both climates, windows with solar control, importance of well designed solar shadings combined with right window geometry,…); therefore the use of such computing tools is able to effectively support the accurate evaluation of many different design alternatives and better control the interaction between the design variables.

Further research activities may be done in order to integrate the comfort indexes into a multi-objective function. To do so, a refinement of the comfort indexes should be done (integrating for example the DGI for the visual comfort) and the trade-off between the comfort optimization and the energy performance may be studied.

Appendix A. Tables related to section 3.1

Table 1. Parameters: definition, variability range and step

Parameter name	Parameter Description	Unit	Variation	Range	Step
MT	Wall construction typology	[-]	Choice between options	M1 – M2 M3 – M4	-
RT	Roof/ceiling construction typology	[-]	Choice between options	R1 – R2 R3 – R4	-
WT	Window typology	[-]	Choice between options	W1 – W2 – W3 – W4 W5 – W6 – W7 – W8	-
Tins,w	Thickness of external insulation on external wall	[m]	Discrete	0.01 – 0.21	0.02
Tins,r	Thickness of external insulation on roof	[m]	Discrete	0.01 – 0.21	0.02
□wall	Absorption coefficient of external wall's outer face	[%]	Discrete	20 - 90	35
□roof	Absorption coefficient of roof's outer face	[%]	Discrete	20 - 90	35
Bwin	Width of glazed area	[m]	Discrete	5.00 – 7.50	0.25
Hwin	Height of glazed area	[m]	Discrete	1.00 – 2.00	0.20
Dsh,ov	Depth of overhang shading system	[m]	Discrete	0.00 – 2.00	0.20
Dsh,vfL	Depth of left vertical fin shading system	[m]	Discrete	0.00 – 2.00	0.20
Dsh,vfR	Depth of right vertical fin shading system	[m]	Discrete	0.00 – 2.00	0.20

Table 2. Envelope type description for CSM design optimization in Turin

Type	Description / Layers (int - ext)
M1	Massive wall (Umin = 0.33 W/m2K): Plaster (1 cm) + Concrete blocks (25 cm) + Insulation ((8 + Tins,w) cm, λ=0.034 W/mK) + Plaster (1 cm)
M2	Lightweight wall (Umin = 0.33 W/m2K): Plasterboard (2.5 cm) + Insulation (10 cm) + MDF (2 cm) + Insulation (Tins,w cm, λ=0.034 W/mK) + Plaster (1 cm)
R1	Massive roof (Umin = 0.30 W/m2K): Plaster (1 cm) + Concrete (20 cm) + Insulation ((12 + Tins,r) cm, λ=0.034 W/mK)
R2	Lightweight roof (Umin = 0.30 W/m2K): Plasterboard (2.5 cm) + Insulation (12 cm) + MDF (2 cm) + Insulation (Tins,r cm, λ=0.034 W/mK)

Table 3. Envelope type description for CSM design optimization in Palermo

Type	Description / Layers (int - ext)
M3	Massive wall (Umin = 0.48 W/m2K): Plaster (1 cm) + Concrete blocks (25 cm) + Insulation ((4 + Tins,w) cm, λ=0.034 W/mK) + Plaster (1 cm)
M4	Lightweight wall (Umin = 0.48 W/m2K): Plasterboard (2.5 cm) + Insulation (5 cm) + MDF (2 cm) + Insulation (Tins,w cm, λ=0.034 W/mK) + Plaster (1 cm)
R3	Massive roof (Umin = 0.38 W/m2K): Plaster (1 cm) + Concrete (20 cm) + Insulation ((7 + Tins,r) cm, λ=0.034 W/mK)
R4	Lightweight roof (Umin = 0.38 W/m2K): Plasterboard (2.5 cm) + Insulation (8 cm) + MDF (2 cm) + Insulation (Tins,r cm, λ=0.034 W/mK)

Table 4. Window type description for CSM design optimization in Turin

Type	Description	U-value [W/(m^{2}K)]	g-value [-]	□ glass [-]
W1	6/16/6 Double glazing, Argon gas, low emissivity, with solar control	1.16	0.265	0.39
W2	4/16/4 Double glazing, Argon gas, without solar control	1.24	0.642	0.76
W3	6/12/4/12/4 Triple glazing, Argon gas, low emissivity	0.70	0.222	0.43
W4	4/16/4/16/4 Triple glazing, Argon gas, without solar control	0.70	0.501	0.64

Table 5. Window type description for CSM design optimization in Palermo

Type	Description	U-value [W/(m2K)]	g-value [-]	□ glass [-]
W5	6/16/4 Double glazing, Argon gas, with solar control	2.54	0.440	0.47
W6	4/16/4 Double glazing, Air, without solar control	2.83	0.755	0.82
W7	6/16/6 Double glazing, Argon gas, low emissivity, with solar control	1.16	0.265	0.39
W8	4/16/4 Double glazing, Argon gas, without solar control	1.24	0.642	0.76

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